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Provisional Geologic Map of Augustine Volcano, Alaska

by

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CONTENTS

Cover photograph. View south-southwest of Augustine volcano in July 1990. Hummocky coastal debris in foreground is deposit of great landslide (debris avalanche) that removed summit of volcano at start of 1883 eruption and flowed into the sea. Five subsequent dome-building eruptions (1883, 1935, 1963–64, 1976, 1986) have restored summit to its pre-1883 height and steepness.

ILLUSTRATIONS

TABLES

CORRELATION CHART **44**

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A very remarkable mountain, rising with a uniform ascent from the shores to its lofty summit, which is nearly perpendicular to the centre of the island . . . . Towards the seaside it is very low, from whence it rises . . . with a rather steep ascent, and forms a lofty, uniform, and conical mountain, presenting nearly the same appearance from every point of view, and clothed with snow and ice, through which neither tree nor shrub were seen to protrude . . . .

— Peter Puget, *Chatham*, May 1st,1794 (Vancouver's "Voyage of Discovery": Lamb, 1984)

INTRODUCTION

Augustine volcano lies in southwestern Cook Inlet, southcentral coastal Alaska, 280 km southwest of Anchorage (figs. 1 & 2). The nearly circular island is 12 km wide east-west, 10 km north-south; a nearly symmetrical central summit peaks at altitude 1254 m. From aerial photographs flown in August 1990, the U.S. Geological Survey's National Mapping Division at Vancouver, Washington, scribed a new topographic map of Augustine Island at 1:25,000 scale with a 10-m contour interval, on which a new geologic map is plotted (plate 1).

Geologic mapping was done in the field over 7 brief seasons between 1988 and 1995, the map data plotted on vertical aerial photographs flown in September 1986 and August 1990. Comparison with photographs flown in August 1976 helped distinguish some look-alike deposits of the 1976 and 1986 eruptions having similar distributions. From the aerial photographs the map was compiled with an analog Kern PG-2 stereoplotter.

Landslide Paradigm

Augustine's summit consists of several overlapping domes emplaced during many historic and prehistoric eruptions. Most fragmental debris exposed in coastal exposures comprise angular blocks of dome-rock andesite typically of cobble to boulder size but carrying clasts as large as 4 to 8 m, rarely as large as 30 m. The surface of such deposits is hummocky, a field of steep conical mounds and intervening depressions with many meters of local relief. En route to Katmai in 1913, Griggs (1920, p. 341) had briefly inferred landslide (debris avalanche) as the origin of Augustine's hummocky coastal topography about Burr Point, by geomorphic analogy with the hummocky and blocky deposit of a 1912 landslide near Katmai.

Several other reports noted hummocky, coarse deposits on the flanks of several Pacific volcanoes: Bandai-san and Yatsugatake in Japan, Galunggung and Raung in Indonesia, and Ruapehu, Egmont, and White Island in New Zealand; such deposits had been inferred to originate suddenly by landslide or "lahar". These volcanic examples were summarized and discussed in textbooks (Cotton, 1944, p. 247–253; Macdonald, 1962, p. 180). In nonvolcanic mountain valleys famous historic catastrophic landslides—at Elm, Switzerland in 1881, at Frank, Alberta in 1903, at Gros Ventre valley, Wyoming in 1925—had also formed coarse blocky deposits with similarly hummocky topography; a gigantic prehistoric endmember at Saidmarreh, Iran became known and discussed (Harrison and Falcon, 1937, 1938; Oberlander, 1965, p. 61–62, 155–156). These phenomena figured in syntheses and in geomorphology textbooks (Sharpe, 1938, plates 1 & 8; Thornbury, 1954, p. 90–93). But unaware of Griggs's obscure paragraph and unattuned to geomorphic literature and textbooks, students of Augustine in the 1970s did not admit landslide to that volcano's seminal processes (Detterman, 1973; Johnston, 1978; Kienle and Swanson, 1980).

Figure 1. Index map of Cook Inlet, Alaska. Augustine volcano constitutes most of Augustine Island.

The hummocky deposits on Augustine's lower flanks resemble both topographically and lithologically those of the great landslide or debris avalanche that initiated the spectacular 18 May 1980 eruption of Mount St. Helens (Voight, 1981; Voight and others, 1981). The deposit of that landslide revealed to all the origin of coarse diamicts with hummocky topography at other stratovolcanic cones. Since 1980 many hummocky coarsely fragmental deposits on Augustine's lower flanks have come to be interpreted as deposits of numerous great landslides and debris avalanches. Table 1 summarizes themes of geologic reports about Augustine that precede the present map.

Acknowledgments

Several colleagues aided our knowledge of Augustine or shared in logistics: Michael P. Doukas, Jack Kleinman[1], Tom L. Murray, John A. Power, Christopher J. Nye, and Samuel E. Swanson. Collaborating or assisting in the field at various times were Hiroki Kamata[2], Robert G. McGimsey, Michael P. Doukas, Cynthia A. Gardner, and Christina A. Neal. Lee Siebert kindly lent official correspondence of George Davidson in 1884 that he had discovered in USC&GS archives at Washington.

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PROCESSES AND DEPOSITS

Augustine volcano consists of materials emplaced by different processes, summarized in the following paragraphs (fig. 3).

A *lava dome* forms when magma extrudes too “stiff” to flow much, thus having slopes as steep as 40° and more. A dome also grows by injection of magma, swelling as an inflating balloon. A succession of more than six domes form Augustine's summit area, others are buried within, and three others protrude high on its flanks. A growing dome sheds hot, lithic bouldery avalanches (lithic pyroclastic flows) that flow to the lower volcano flanks.

A *lava flow* has less viscosity than flows of a lava dome and thus flow farther downslope. Augustine reveals only a few short lava flows, the most obvious at midlevel on the north flank.

Expanding, escaping gas violently fragments magma rising in the vent, and the dense mixture of gas and rock erupts explosively. The erupted material flows rapidly down the volcano flank as a *pyroclastic flow*, consisting mostly of gas and pumice fragments but also bearing rock fragments. The resultant *pyroclastic-flow deposit*, consists mostly of sand-size particles but can include large boulders; some are rich in low-density pumice blocks that during flow “float” to its top and sides. Pyroclastic flows shed from an emplacing dome consist mostly or entirely of nonpumiceous (“lithic”) rock fragments.

Fragmented magma, along with accidental material eroded from vent walls, is carried up in a vertical eruption column and then falls out as angular clasts of pumice and rock fragments. Some material falls broadly on the volcano flanks; most it is carried to particular azimuths by wind. The term *tephra* denotes material deposited from such a fall regardless of its grain size. On the volcano flanks the clasts can be decimeters in diameter; typically grain size decreases logarithmically downwind. A few tephra layers on Augustine are 0.5 to 1 m thick and with fragments as large as several centimeters; many others are much thinner and of sand-silt ash.

Figure 2. Augustine Island. Most place names are informal but are needed in present report for locations and designation of geologic map units. Mostly informal place names proceed north from summit then clockwise around coast. SD, summit-dome complex; NSL North Slope lava flow; BP, Burr Point; NEB, Northeast Bench; NEP, Northeast Point; YC, Yellow Cliffs; EP, East Point; SEP, Southeast Point; SEB, Southeast Beach; SP, South Point; KD, Kamishak Dome; LB, Long Beach; WL, West Lagoon; WI, West Island; NWL, Northwest Lagoon; GP, Grouse Point; NB, North Bench; RP, Rocky Point.

Blocks are also sometimes ejected explosively and travel outward on *ballistic* trajectories. They may be ejected to any azimuth, including windward.

Rarely during magma intrusion high into the volcanic cone, the steep summit area of a volcano becomes so mechanically unstable as to fail as a huge landslide or *debris avalanche*. On the lower volcano flanks a debris-avalanche deposit has a hummocky surface with as much as tens of meters of relief and comprises fragments of the summit dome(s) ranging from small boulders to rare 30-m internally fractured megablocks. Most of the outer flanks of Augustine volcano consists of coarse, lithic diamicts, many of them as thick as 10 m and more, and with hummocky topography. Contrasting other stratovolcanoes, debris avalanche is a fairly common process at Augustine.

Hot pyroclastic debris rapidly mixing with and melting seasonal snowpack can adsorb enough water to transform into a mass flowage of wet, muddy rock debris called a *lahar*. A lahar typically is rich in large boulders

Table 1.—*Summary of previous geologic work about Augustine volcano*

Reference	**Topic**
Davidson, 1884	Summary of observed effects of 6 October 1883 Augustine eruption
G.E., Davidson, (unpub. letter 6 Nov. 1884)	Relates direct observation in June 1884 by a Capt. Cullie that N. flank Augustine slid as cataclysmic landslide into sea on 6 Oct. 1883
Becker, 1898	Direct observations of flanks and crater after 1883 eruption
Griggs, 1920	Brief stop at Augustine, interprets Burr Point deposit as landslide (obscure reference)
Coats, 1950	Listing of Aleutian-arc volcanoes and summary of historic eruptions
Detterman & Reed, 1964	Geologic map at 1:250,000 including Augustine Island (generalized)
Detterman, 1968	Summary of observed effects of 1963–64 Augustine eruption
Detterman, 1973	Geologic map at 1:63,360 of Augustine Island
Kienle & Forbes, 1976	Summary of observed effects of 1976 Augustine eruption
Buffler, 1976	Map and stratigraphy of Mesozoic rocks, south flank Augustine Island
Johnston, 1978	Summary of historic eruptions; 1976 eruption chronology, processes, and petrology of erupted materials
Johnston, 1979	Evidence that Augustine volcanism began during the late Pleistocene
Johnston & Detterman, 1979	Summary of historic eruptions; deletion of spurious “1902 eruption”
Kienle and Swanson, 1980 [reprinted 1985]	History of Augustine volcano, hazards (mostly pyroclastic flow, lahar, and dome growth)
Kienle & Swanson, 1983	Plate-tectonic setting and petrology, including Augustine
Siebert, 1984	Documentation of Mount St. Helens-type debris avalanches off many volcanoes, including Augustine
Kienle, Davies, Miller, Yount, 1986	Summary of chronology and observed effects of 1986 Augustine eruption
Daley, 1986	Petrology, petrography, geochemistry of Augustine domes and lava flows
Reeder & Lahr, 1987	Seismic evidence for behavior and timing of Augustine 1976 eruption
Siebert, Glicken, Ui, 1987	Debris avalanches and consequent lateral blasts and tsunamis at many volcanoes, including Augustine
Kienle, Kowalik, & Murty, 1987	Numerical simulation of 1883 Augustinian tsunami
Swanson & Kienle, 1988	Comparison of 1986 Augustine eruption with hazards report of Kienle and Swanson (1980)
Siebert, Glicken, & Kienle, 1989	Concept of debris avalanche forming flanks of Augustine volcano; details on prehistoric West Island and 1883 Burr Point debris avalanches

Table 1.—*Summary of previous geologic work about Augustine volcano—continued*

Kamata, Johnston, & Waitt, 1991	1976 eruption chronology, effects, deposits, and stratigraphy
Beget & Kienle, 1992	Teprha- and ^{14}C-dated 12 Augustine debris avalanches in last 2000 yr; early deposits >40,000 yrs
Siebert, Begét, & Glicken, 1995	Details of debris-avalanche deposits on north flank

but contains all grain sizes down to sand, silt, and even clay. The more viscous lahars leave paired sharp lateral levees and have steep, lobate termini. It is difficult from the lithology and geomorphic character of surface exposures to distinguish a bouldery lithic diamict emplaced as lithic pyroclastic flow (dry flow) from one emplaced as debris-flow lahar (wet flow). Geomorphically both can be leveed and with steep, intricately lobate, bouldery termini.

Storm waves wash all of Augustine's coasts, removing debris finer than cobbles from headlands, including newly deposited tongues of pyroclastic flow or lahars, and leaving a bouldery *beach deposit.* In reëntrants between headlands, wave-winnowed sandy beach deposit accumulates. Some of the sand is in turn reworked by wind into *eolian sand dunes* at the back of the beach above maximum wave height.

ROCK TYPES

In hand specimen and thin section, Augustine dome and lava-flow rocks are plagioclase-porphyritic andesite ranging from dark gray to light gray to reddish (oxidized). Deposits of debris avalanches, debris flows, and pyroclastic flows consist of or contain boulders and smaller fragments of porphyritic andesite, to the eye identical to summit-dome rocks. On the south flank are rare inliers of fragmental olivine basalt.

Chemically analyzed Augustine rocks scatter across the SiO_2 field of andesite of Le Bas and others (1986) and of LeBas and Streckeisen (1991, fig. 5) (fig. 4). A few analyzed whole-rock samples range down into the basaltic-andesite field or up to the dacite field. The glass fraction of pumice fragments ranges from dacite to rhyolite. For each of six coarse pumice layers of the last 2000 years, the most silicic of the glass analyses is well into the rhyolite range (>72% SiO_2).

GRAIN SIZE AND SHAPE

Grain sizes are designated by the standard Wentworth classifications for sediments. These and shape designations (such as angularity) are as by Folk (1980). A designation such as “pebbly sand” denotes solely grain size, having no implication whatever about genesis or emplacement mechanism.

CHRONOLOGY

Radiocarbon Ages

We have obtained 47 radiocarbon ages from organic materials interbedded with tephra deposits on Augustine Island (table 2). In such a layered sequence, a dated organic sample immediately overlying a tephra provides a minimum-limiting age on that tephra; one from just below provides a maximum-limiting age. Most radiocarbon ages directly limit the age of tephra layers. But once age-bracketed by radiocarbon dates, a distinguishable tephra layer becomes a useful date by proxy. Table 3 depicts a generalized composite stratigraphy of Augustine's debris-avalanche deposits with respect to the main tephra deposits.

Tephrochronology

Tephra sequences 1- to 3.5-m thick are relatively continuous along the east, southeast, and south coasts of Augustine Island. These azimuths are generally the downwind direction where tephra tends to accumulate, but also these directions are where the lower-flank deposits are generally older than on other flanks. Upper Holocene stratigraphy established in these most complete sections show seven or eight coarse pumiceous layers

Table 2.—*Stratigraphy of radiocarbon ages and*

tephra layers at Augustine volcano

Radiometric Ages (& tephra deposits)	Lab. No.	Reference †
101.7±0.7 [mod.]	B–55672	This study
<185	I–14992	BK92
≤185	I–14923	BK92
140±60	B–24773	BK92
170±70	B–24779	BK92
195±115	?	SK88
205±90	I–14924	BK92
280±100	B–24781	BK92
330±145	?	SK88
380±20	QL–4808	This study
(Teprha layer B)		
367±55	?	SGK89
410±50	B–24777	BK92
450±80	B–28536	BK92
470±140	?	SK88
490±70	B–24776	BK92
730±60	B–28537	BK92
(Tephra layer M)		
400±50	B–55673	This study
710±50	B–55667	This study
760±60	B–55662	This study
770±50	?	BK92
800±60	B–55663	This study
800±120	?	SK88
860±80	B–24780	BK92
1,000±100	B–24780	BK92

Table 2.—*Stratigraphy of radiocarbon ages and tephra layers at Augustine volcano—continued*

Radiometric Ages (& tephra deposits)	Lab. No.	Reference †
(Tephra layer C)		
320±60	B–55665	This study
1,100±70	B–58976	This study
1,130±50	B–28535	BK92
1,195±120	?	SK88
1,200±140	?	SK88
1,290±80	B–28539	BK92
1,400±50	B–28534	BK92
1,420±60	B–28538	BK92
1,020±50	B–55666	This study
(Tephra layer H)		
1,190±80	B–57901	This study
1,470±160	?	BK92
1,500±155	?	BK92
1580±20	QL–4811	This study (distal)
1,610±70	ETH 3826	BK92
(Tephra layer I)		
1725±25	QL–4812	This study (distal)
1,830±80	B–24775	BK92
(Tephra layer G) ♯		
2,160±60	B–55674	This study
3360±25	QL–4812	This study (distal)
(Distal Augustine tephra)		

Table 2.—*Stratigraphy of radiocarbon ages and tephra layers at Augustine volcano—continued*

Radiometric Ages (& tephra deposits)	**Lab. No.**	**Reference †**
3620±25	QL–4812	This study (distal)
6210±70	B–55676	This study
7170±60	B–55675	This study
≥39,890*	ETH 7166	BK92
≥40,440*	ETH 7167	BK92

† BK92, Begét and Kienle (1992); SGK89, Siebert and others (1989); SK88, Swanson and Kienle (1988)
♯ Stratigraphic relations of tephra G to the three dates listed just below it are uncertain
* AMS date

stratigraphically superposed, some with intervening fine (sand- or silt-sized) tephra layers. In upward stratigraphic order (fig. 5) the coarse layers are designated layers G, I, H, C, O, M, and B. (Layer O is rare, its origin and significance obscure.) Within scattered inlier sections of older debris lie several additional layers that are not easily correlated from place to place.

In 1995 James R. Riehle and Charles E. Meyer (written commun., 1995) microprobed glass from 31 samples of Augustine coarse proximal tephra for eight major elements. These data support many of the correlations based on field stratigraphy and also suggest correlations with parts of some of the inlier sections. But they also show that several superimposed tephras are chemically heterogeneous and that some of their compositional ranges overlap each other. For instance, tephra layers C and M give essentially identical results, as close as replicate analyses of either layer M or layer C. Further analyses of these and of comparable data by J.E. Begét are underway. Correlation of tephras between separated localities is thus by field stratigraphy, in a few places augmented by the microprobe data.

Limitations of this stratigraphic method are several. The identification of the lowest tephra in a sequence is critical to deciphering the age of an underlying deposit. Parts of the tephra sequence are readily distinguishable in the field—thus tephra C commonly is a couplet, and several decimeters of fine-ash beds separate tephra layers I and H. In sections along the south and east coasts that contain several superposed tephra layers, field characteristics are usually sufficient to identify many tephra layers with certainty. But where only one or two tephra layers appear in section, identity can be ambiguous. A tephra can be "missing" at exposed or unstable sites such as the crests of levees and hummocks, sites above vegetation, and slopes steeper than about 15°. Such stratigraphic problems caused by post-emplacement erosion can be overcome only by exploring on any one deposit numerous sites, including some in swales, vegetated areas, and other sites likely to retain a deposited tephra.

Table 3.—*Stratigraphy of tephra layers and debris-avalanche deposits*

Debris-Avalanche Deposit	**Tephra Layer**
Burr Point (AD 1883)	
Rocky Point	
West Island	
Grouse Point	
	B
Southeast Beach	
Lagoon	
	M
North Bench	
	C
Long Beach	
South Point	
	H
Northeast Point	
	I
Southeast Point	
Yellow Cliffs	
	G
East Point	

Figure 3. Sketch showing genetic processes and hazardous phenomena at Augustine volcano. Modified by Bobbie Myers from Myers and Brantley (1995)

Figure 4. Plot of chemical analyses of rocks (whole-rock analyses) and tephra (glass separates) from Augustine Island. Graphed data compiled from Kienle and Forbes (1976), Daley (1986), Swanson and Kienle (1988), Siebert and others (1989), and from selected analyses by James R. Riehle in 1995 of tephra samples collected during present project. Boundaries of named fields according to LeBas and others (1986) and LeBas and Streckeisen (1991, fig. 5).

Geomorphology

Many of the map units are distinguished from neighboring deposits partly by geomorphic relations. Thus one unit eroded back into a straight, high sea cliff must be much older than an uncliffed neighbor of similar material jutting seaward. Sharp levees define the lateral limits of some debris avalanches. A unit far more vegetated than its lithologically similar neighbor at the same altitude must be much older.

Bouldery lithic pyroclastic flows (dry flows) and debris-flow lahars (wet flows) that have flowed less that a few kilometers can be nearly identical in geomorphic expression, as they are in lithology (coarse grain sizes, massive texture, angular clast shapes). Both types of flow typically are gravelly sand or sandy gravel, can have a few meters of local relief, and are leveed and have steep, intricately lobate termini. Yet such geomorphic characteristics help distinguish the two from deposits of other origins—for instance hummocky debris-avalanche deposits.

Unconsolidated debris delivered to the coast from Augustine volcano is eroded back over time by sea waves. Sea cliffs on Augustine's coasts range up to 40 m high where eroded far back into ancient deposits. A sea cliff (fig. 6*A*) ceases to develop when a flowage from a new eruption overrides and spreads beyond the cliff, pushing the coastline seaward (fig. 6*B*). Or a sea cliff can

Figure 5. Tephra stratigraphy overlying flowage deposits just north of Southeast gully about 0.9 km coastwise north-northeast from Southeast Point. The "flowage deposits" are each several meters thick. fs = fine sand; vfs = very fine sand; z = silt.

be surrounded by a flowage down an adjacent valley that then spreads coastwise, isolating the cliff from the sea (fig. 6*C*). Many such sea cliffs lying back from Augustine's present coasts tell of gradual wave erosion arrested when new eruption deposits are emplaced.

SYNOPSIS OF GEOLOGIC HISTORY

In lower Cook Inlet on the flank of a small island of Jurassic clastic-sedimentary rock, Augustine volcano began erupting before the late Wisconsin glaciation (late Pleistocene). The oldest known effusions ranged from explosive eruptions of olivine basalt interacting with water to dacitic or rhyodacitic pumiceous pyroclastic flows. Late Wisconsin piedmont glaciers issuing from the mountainous western mainland surrounded the island at a time when dacitic eruptive debris swept down the south volcano flank.

If Augustine eruptions occurred between the late Wisconsin and about 3600 yr B.P. there is but scant evidence (though deposits may lie offshore). On a few south-flank kipuka inliers, undated but stratigraphically deep pumiceous pyroclastic-flow and -fall deposits may represent this period. On Shuyak Island 100 km southeast of Augustine, distal fall tephra of Augustinian chemical provenance (probe analysis of glass) dates between about 3620 and 3360 yr B.P. (table 2; Riehle and others, 1996).

From somewhat before 2200 yr B.P. to the present, numerous coarse debris avalanches have swept to Augustine’s coast and beyond, most recently in A.D. 1883. The decapitated summit after that eruption and replacement since by andesite domes emplaced during five subsequent eruptions suggests the process by which the many older avalanches occurred: collapse of steep summit domes, replaced by later dome eruptions. The most understood historic example of such volcanic debris avalanches is the great Mount St. Helens landslide of 18 May 1980 (Voight and others, 1981; Voight and others, 1983; Glicken, 1997).

Beneath a tephra layer “G” dated at about 2200–2000 yr B.P. lies a coarse, hummocky debris-avalanche deposit along the east coast, the oldest exposed such deposit on Augustine Island. Between about 2100 and 1800 yr B.P. (between tephra layers G and I) two large debris avalanches swept east and southeast to the sea. Between 1700 and 1400 yr B.P. (between tephras I and H) a large debris avalanche shed east and east-northeast to the sea.

Between about 1400 and 1100 yr B.P. (between tephra layers H and C) one debris avalanche swept to the sea on the south, another on the southwest, and perhaps a third on the north-northwest. Pumiceous pyroclastic fans were shed to the southeast and southwest and lithic pyroclastic flows and lahars(?) to the south and southeast. Between about 1000 and 700 yr B.P. (between tephra layers C and M) pyroclastic flows, pyroclastic surges, and lahars swept the west and south flanks.

Between about 700 and 400 yr B.P. (between tephra layers M and B) a debris avalanche swept to the sea on the west and a small one on the south-southeast. Large lithic pyroclastic flows shed to the southeast; smaller ones descended exiting swales on the southwest and south.

Between about 350 yr B.P. (after tephra layer B) and historic time, three separate debris avalanches swept to the sea on the west-northwest, north-northwest, and north flanks. One of them (West Island) was large and fast, most of it having rode to sea beyond a sea cliff cut back into older deposits. Augustine’s only conspicuous lava flow was emplaced on the north flank.

During this prehistoric period numerous domes must have been emplaced at the summit, repeatedly renewing the source for catastrophic debris avalanches. Remnants of these older domes form the east and south sides of the present summit-dome complex. Below the summit area at least three domes were emplaced on the upper flanks, one on the south (Kamishak dome), two on the northwest (domes “I” and “H”). Another undated and nearly buried dome or lava flow diversifies the upper south flank.

During at least the last 700 years B.P. beach and back-beach eolian dunes accreted at the southwest coast, forming a conspicuous faintly ribbed coastwise topography there.

In historic times an eruption in 1883 shed a debris avalanche to the sea on the north-northeast, followed by pyroclastic flows and surge. Eruptions in 1935 and 1963–64 grew summit domes that spilled respectively over the southwest and south flanks and shed coarse rubbly lithic pyroclastic flow down those flanks. Eruptions and 1976 and 1986 grew domes that draped down the north flank and shed voluminous pyroclastic flows to the northeast through north-northwest flanks. During both eruptions but especially in 1976 m, much smaller pyroclastic flows and (or) lahars swept down valleys on other flanks.

Figure 6. Sketch showing in profile development of arrested sea cliffs at Augustine Island.

A. High sea cliff cut into flowage (such as debris-avalanche) deposit. Wave erosion of this cliff can be arrested by either B. or C.

B. Initial sea cliff is overridden by new flowage deposit, which isolates initial cliff by moving coast seaward; into this deposit a new sea cliff is cut.

C. Initial sea cliff is isolated from sea by a coastwise flow delivered through an adjacent side gully; into this deposit a new sea cliff develops seaward.

PRE-AUGUSTINE MESOZOIC ROCKS

A block of sedimentary bedrock constituted the island before the volcano existed. This bedrock reaches from the south coast to as high as altitude 400 m, the lower 300 m mapped in some detail by Buffler (1976). Constituent invertebrate fossils identifies most of these rocks with the upper Jurassic Naknek Formation (Detterman and Jones, 1974). The Naknek Formation on Augustine Island comprises a lower member of thin-bedded dark-gray siltstone to very fine sandstone and an upper member of cliff-forming thick-bedded, medium to fine sandstone (units *Jnsh and Jns*). Pelecepod fossils lie throughout the section. The bedrock block dips south at a variable 10–36°, mostly at 10–15°. The south dips are despite the subsequent growth of the volcanic edifice that doubtless has isostatically depressed the bedrock northward, flattening the south dips.

The cliff-forming upper sandstone is exposed almost continuously for more than 2 kilometers along strike below about altitude 270 m. At the head of West Kamishak gully lies a newly discovered, poorly exposed patch of highly oxidized sandstone at altitudes 350–400 m, exposed only because the head of the gully is steeply incised beneath a carapace of coarse andesitic rubble many meters thick. This relation suggests that much of the conspicuously smooth slopes lying between sea level and about 500 m and between azimuths south-southeast and south-southwest, including a kipuka to the east, are fundamentally of this bedrock albeit thickly and thoroughly mantled by Augustine debris.

Just west of the continuous Jurassic bedrock, Detterman and Jones (1974) and Buffler (1976) report upper Cretaceous rocks bearing *Inoceramus* fossils. This outcrop seems no longer to exist, perhaps buried by the extensive pyroclastic-flow and laharic deposits of the 1976 eruption.

The Mesozoic rock must have existed as an offshore island before Augustine volcano began to erupt. Reasonable (10–30°) slopes projected north from today's outcrops suggest that the north part of this block lies beneath the Augustine central vent.

Along the south coast of Augustine Island, angular boulders of fossiliferous sandstone are common within the Long Beach debris-avalanche deposit and among the beach boulders derived from it by wave erosion. These sandstone boulders extend as far as 2 km west of the westmost gully that today can convey such blocks from existing outcrops to the coast. This distribution indicates that the Jurassic bedrock lies buried beneath Augustine debris at least 0.4 km northwest of the present limit of outcrop.

Springs emerge at contact of the upper sandstone member with its underlying shale, water that doubtless contributes to retreat and maintenance of the prominent upper cliff. Abundant water on a layered sequence sloping gently toward a steeply incised face is a circumstance conducive to landsliding, which indeed seems to have occurred to cause a highly fractured block, apparently of the upper sandstone member, lying at the coast (map unit *Pl*).

PLEISTOCENE DEPOSITS

Pleistocene-age materials crop out sporadically on the south flank, comprising a landslide block, glacial deposits, and volcanic materials.

Volcanic Rocks

Several small inliers on the south volcano flank expose bedded dark, basaltic fragmental material whose beds 1 to 30 cm thick alternate between medium sand and granule gravel, generally poorly sorted (unit *Pvb*). Some beds that contain much mud-sized material are tightly cemented. Fragments of porphyritic olivine basalt as large as 20 cm are scattered through the sections. Most fragments are very angular, but a few are subangular to subround, distinctly abraded.

A few beds have low-angle cross beds; some laminae contain mud balls (accretionary lapilli) 3 to 8 mm in diameter, and some beds contain angular bombs as large as 20 cm whose impact sagged underlying beds as much as 25 cm. These characteristics, the blocky shape of apparently juvenile clasts, and retention of fine sand and silt in many beds are evidence that water was the main propellant in the explosions and that at least some of the beds were wet during emplacement. Such deposits are commonly called “hyaloclastite”.

Olivine-basalt hyaloclastite at altitude about 300 m is overlain by about 10 m of white pumiceous beds (unit *Pvr*) ranging from openwork, angular pumice pebbles (fall bed) to pebbly sand with subangular pumice clasts (pyroclastic-flow deposit). The lowest pumiceous beds of very coarse sand are interlaminated with the upper 20 cm of the basaltic hyaloclastite beds. At the westmost inlier volcanigenic beds both overlie and underlie glacigenic beds bearing exotic stones (scale too small to show on map; see discussion below).

Landslide Block

A block along the south coast just east of the mouth of West Kamishak Creek is 500 m long and 60 m high of nearly intact sandstone of the upper member of the Naknek Formation, which lies *in situ* 200 m higher. Compared to unambiguously *in-situ* rock, the coastal block (unit *Pl*) contains far more plentiful small faults and joints, many of them open fissures. Also, attitude of bedding in the coastal block is highly variable, evidence that many sub-blocks have rotated with respect to each other. Despite its size, it seems clearly a block landslide, as Buffler (1976) also infers but Detterman (1973) does not.

Glacial Deposits

Scattered surface exotic stones or diamicts containing exotic stones, some of them glacially striated, crop out at several places on the south flank (unit *Pg*). These stones range from angular to rounded and from pebbles to boulders as large as 1.6 m. Among the diverse rock types are granite, granodiorite, diorite, quartz diorite, gabbro, diabase, porphyritic dikerocks, granite-gneiss, hornfels, greenstone, amphibolite, vein quartz, banded limestone and chert, and argillite. All the stones are unweathered and hard, clearly of the last (late Wisconsin) glaciation and not an older one. Hamilton and Thorson (1983, p. 46–47) summarize radiocarbon dates indicating that the late Wisconsin glaciation in Cook Inlet region occurred between about 30,000 and 12,000 ^{14}C yr B.P. The scattered debris on Augustine Island containing exotic stones lie between altitudes 120 and 290 m but apparently no higher. This altitude may register the height to which coalesced late Pleistocene piedmont glaciers from western mountains filled lower Cook Inlet and banked against Augustine Island, perhaps about 15,000 years ago (see Hamilton and Thorson [1983, fig. 2.4] for generalized illustration). Johnston (1979) reported exotic stones as high as 320 m on a spur 1 km north of South Point, but the range of unarguably glacial exotic stones in that area is 230–275 m, similar to that on a spur 1.6 km farther west (250–290 m). The exotics Johnston reported higher are much smaller, far better rounded, and apparently derived from congomerate beds upslope within the upsection part of the Jurassic Naknek Formation.

A section at 10–30 m altitude overlying the south-coastal landslide block (unit *Pl*) includes exotic-bearing outwash of chiefly volcanic debris (unit *Pog*), and an interbedded primary pumiceous fall deposit from Augustine. The outwash includes pumiceous gravel dipping as steeply as 38° northward and northeastward. These onshore dips imply glacier ice contemporaneously banked against the south side of a largely unglaciated Augustine Island, perhaps during ice thinning and recession. The dips steeper than repose angle suggest settling and rotation during melting of formerly adjacent or underlying glacier ice.

At altitude about 300 m along Augustine Creek (westmost of the Pleistocene sections) the lowest exposed bed of a section of alternating tephra and pumiceous pyroclastic-flow deposit is waterlaid pumice from which wood and charcoal fragments yield two AMS radiocarbon ages greater than 39,000 yr B.P. (table 2). This bed is overlain by a bed of glacial outwash—so inferred by its content of exotic stones—which is overlain by a pumiceous (Augustine) bed. Thus some of the Pleistocene-age glacial and volcanic materials perhaps predates the late-Wisconsin glaciation of Cook Inlet.

DEPOSITS OF LATE PLEISTOCENE TO LATE HOLOCENE AGE

Fall and Pyroclastic-Flow Deposits (unit *PHfp*)

Exposed on the steeply eroded sides of three south-side inlier kipukas at altitudes 250–700 m are 8–10-m sections comprising several beds of pumiceous and lithic pyroclastic-flow deposits interbedded with many beds of loose, sorted pumiceous fall deposit. The uppermost pumiceous fall beds probably correlate with tephras M, C, and perhaps with other tephra beds of the coastal sections, though ambiguous field character and ambiguous chemical data make such correlation tenuous. Yet a radiocarbon age of about 2160 yr B.P. (table 2) from the upper midsection (below the upmost few tephra layers) at the eastmost such section supports the tenuous correlation.

The lowest parts of these inlier-kipuka sequences in places overlie Pleistocene glacial deposits (bearing exotic stones) and are probably Pleistocene in age. From the lowest exposed pumiceous bed from the westmost of these sections, two AMS radiocarbon dates exceed 39,000 yr B.P. (table 2).

LAVA DOMES OF UNCERTAIN LATE HOLOCENE AGE

Kamishak Dome (unit *dk*)

Kamishak dome forms a conspicuous bump on the south volcano flank topping at altitude 513 m. It is thickly blanketed by younger fall and ballistic debris leaving the only exposure on its steep south face. The rock consists of light-gray porphyritic andesite containing about 15 percent plagioclase phenocrysts and 3 percent hornblende phenocrysts. Because even the upper part of the dome seems to be overlain by considerably less than the more than 10 m of fragmental deposits that lie locally farther downslope, it seems to be of late Holocene age.

Domes “I” and “H” (units *di* and *dh*)

Two domes of porphyritic gray andesite form conspicuous topographic bumps at altitudes 1025 and 910 m on the upper northwest flank, some 400 to 800 m northwest of the central summit-dome complex. The large West Island debris avalanche (table 3) must have left a large crater including this area, so the domes must be younger than about 350 yr B.P. (age of B tephra, table 2), though they precede the historic eruptions.

Prehistoric Summit Dome(s) (unit *ds*)

Probably several domes comprise the east and south sides of the summit cone. Three overlapping domes are distinguished by slight variations in overall color separated by shallow topographic moats. Part of the east side is deeply eroded into the “pinnacles”, which on a 1909 photograph (Kienle and Swanson, 1980, fig. 10; Swanson and Kienle, 1988, fig. 5) is rock beheaded by a summit collapse during the 1883 eruption. This old dome rock is overlapped by the several historic domes: the south side by the 1964 dome, the west side successively the 1883 (buried), 1935, and 1964 domes.

Lava Flows (unit *ld*)

Massive porphyritic andesite crops out below the level of summit and subsummit domes at 4 sites on the south and north flanks. Largely buried by younger fragmental debris, these inliers crop out only in small patches that have diminished even in recent decades. They are far enough downslope to be classed as “lava flows”, and in form they seem not to be large mounds, though the porphyritic andesite is like that of the domes.

DEPOSITS OF LATE HOLOCENE AGE (PREHISTORIC)

Most of Augustine's exposed apron of coarse debris is younger than 2500 years. Overlying and intercalated pumiceous fall deposits, partly dated by radiocarbon, give some limits to timing and correlation of most deposits. Most of the volume of flank deposits comprises bouldery diamicts of angular clasts of porphyritic andesite. Each diamict is an unsorted, unstratified mixture of angular clasts of all sizes from sand to enormous boulders. Most or all clasts are of scarcely vesicular porphyritic andesite similar to rock of the present dome complex. Many of the diamicts contain a minor constituents derived from (a) Mesozoic rocks that buttress the south volcano flank and (b) their sporadic veneer of Pleistocene deposits.

Small-scale topographic character helps to identify emplacement mechanisms by debris avalanche on the one hand, or by debris flow or lithic pyroclastic flow on the other. The surfaces of many flank deposits are scarcely hummocky but are delicately multilobate and leveed. These forms are typical of high-resistance pyroclastic flows and debris-flow lahars. The surfaces of a few deposits are smooth and sloping gently seaward, denoting a flowage such as by low-resistance pyroclastic flow, lahar, or alluvium.

The surface form of the very coarse deposits along most of the coast is hummocky with local relief of many meters. The hummocky topography and huge angular constituent boulders mimic the deposit of a huge landslide (debris avalanche) that initiated the paroxysmal 18 May 1980 eruption of Mount St. Helens, Washington (Voight and others, 1981; Glicken, 1986). The numerous, hummocky coarse deposits at Augustine, some as thick as 30 m, must have a similar origin by debris avalanche.

A continuous high sea cliff between Southeast Point and Northeast Point exposes bouldery diamicts below the H tephra that by color and relation to tephra layers we separate into four units, all apparently deposits of debris avalanche. All are clearly fragmental but contain angular boulders as large as 8 m and rare shattered megablocks much larger. The angularity and large size of blocks confused Detterman (1973): lacking the concept of debris avalanche, he mapped this 6-km segment of coast as *in-situ* lava flows.

Deposits Older than G Tephra (2500?–2100? yr B.P.)

East Point Debris-Avalanche Deposit (unit *G-a*)

A diamict forming the lowest part of coastal sea cliff for 3 km along the east coast is at least 13 m thick (base not exposed). It contains angular andesite fragments as large as 5 m; on the beach before the sea cliff are wave-winnowed lag boulders as large as 7 m. The large clasts are set in a gravelly-sand matrix of shattered andesite, generally gray but in places oxidized reddish. Most of the boulder-sized andesite clasts are gray, some are reddish, and a few are highly altered to yellow or white. A few delicate, prismatically jointed clasts must have been hot juvenile dome-rock clasts that cooled after emplacement.

The deposit is capped by the sparsely exposed G tephra, and that overlain by the highly oxidized bouldery diamict of Yellow Cliffs debris-avalanche deposit.

Deposits Between G and I Tephras (2100?–1800? yr B.P.)

Yellow Cliffs debris-avalanche deposit (lower part of unit *GIays*)

Overlying the G tephra (sparsely exposed) that caps the East Point debris-avalanche deposit is a highly oxidized massive diamict containing angular altered andesite boulders commonly 1–2 m in diameter, some as large as 3.5 m. This distinctively yellowish unit 5 to 9 m thick forms the middle to upper part of the sea cliff for at least 2.5 km along the east coast. The matrix and large clasts alike are strongly altered to soft zeolite(?) and clay. But the unit also contains sporadic pods meters in diameter of gray to reddish coarse diamict of scarcely altered andesite. Midway between East Point and Northeast Point its surface shows sharp local relief of 3–4 m where directly buried by the Northeast Point debris-avalanche deposit. At and south of Southeast Point the Yellow Cliffs diamict is overlain by the gray Southeast Point debris-avalanche deposit, which is capped by the I tephra.

The hummocky surface topography and the massive and coarse texture clearly identify the Yellow Cliffs diamict as a debris-avalanche deposit. The enclosed pods of unoxidized diamict and the fact that the unit is both overlain and underlain by unoxidized to weakly oxidized similar diamicts shows that the heavy alteration had occurred before the avalanche.

Southeast Point debris-avalanche deposit (upper part of unit *GIays*)

Overlying the Yellow Cliffs diamict and beneath tephra layer I along the coastal cliff 350 m west of Southeast Point lies a diamict at least 8 m thick with *in-situ* boulders as large as 3.5 m, and winnowed ones on the beach below as large as 7.5 m. The angular clasts are gray to reddish and scarcely altered, contrasting the underlying Yellow Cliffs diamict. The deposit extends at least 2.5 km northeast along the coastal cliffs to East Point, where it is also overlain by the I tephra and that, in turn, overlain by the Northeast Point debris-avalanche deposit. The surface slope at top of sea cliff, if projected seaward, indicates that deposit has been wave eroded back at least 0.5 km, perhaps 1.5 km. Relations among four debris-avalanche deposits—two of this map unit, one of the overlying unit, one of the underlying unit—are shown schematically by figure 7.

Deposits Between I and H Tephras (1700–1400 yr B.P.)

Northeast Point debris-avalanche deposit (unit *IHa*)

Underlying the H tephra, a coarse and massive diamict extends coastwise for more than 4 km from north of Northeast Point to south of East Point. The deposit contains angular boulders of gray andesite as large as 7 m in intermediate diameter. The surface is broadly hummocky, having a relief of 3 m over distances of 50 m. At East Point it is at least 20 m thick (base not exposed); it tapers south 1.5 km south of East Point to 7 m thick, from where it pinches out within a few hundred meters.

Figure 7. Schematic sketch of coastal cliffs along east side of Augustine Island showing stratigraphic relations of four oldest debris-avalanche deposits and the three oldest of the coarse pumiceous-tephra “marker beds”.

Its south part overlies three older debris-avalanche deposits (see above). The north side of the main body of deposit is delineated by a straight levee 3–8 m high. But similarly hummocky, bouldery deposit also lies north of (outside) this levee. This northern bouldery debris may also be part of the Northeast Point debris avalanche, but of a phase that immediately preceded the levee-forming phase. This coarse rubbly diamict is exposed in the walls of incised gullies upslope, apparently tracable up to the base of the summit dome complex. Mantling tephra (lowest coarse tephra = H) and humus three meters and more thick have considerably smoothed this topography. But beneath this mantle in coastal exposure it has a sharp local relief of at least 6 m over distances of 20 m. A few boulders larger than 2.5 m in the top of the deposit protrude through the thick tephra-humus blanket.

About 0.8 km south of Northeast Point the upper part of the deposit is strikingly monolithologic, every fragment angular, only a low proportion finer than pebble size. Here the deposit appears to be a single dome block at least 30 m long; it is more disaggregated than so-called “jig-saw” blocks in the 1980 Mount St. Helens avalanche described by Glicken (1986), yet it did not dilate and disaggregate enough to form or admit matrix. This huge block must have piggybacked more or less intact atop the moving avalanche, for such a gigantic block cannot have been moved by pyroclastic flow or lahar. Detterman (1973) mistook this bouldery fragmental deposit, like the others along this coast, for *in-situ* lava flow.

At Northeast Point the deposit crosses a straight east-facing scarp 650 m long and 30 m high that lies about 450 m back from the sea at Northeast Point. This sea cliff had been cut into the Yellow Cliffs (and older?) debris-avalanche deposits. The capping section including a lowermost coarse pumice (layer H) is the same before the scarp as it is behind. Thus the scarp was overridden and buried by the Northeast Point debris avalanche albeit not thickly enough to obliterate it utterly (fig. 6*B*). The debris-avalanche deposit is at least 20 m thick (base not exposed) seaward of the buried sea cliff whose original height therefore must have been at least 40 m.

Nearly continuous boulders, some as large as 5 m, extend at least as far as 600 m offshore of Northeast Point, showing that the original deposit has been eroded back at least that far into its present sea cliff.

Northeast Bench debris-avalanche or lahar deposit (unit *IHl*)

A bouldery gravel diamict (unit *IHl*) containing angular porphyritic andesite stones as large as 4 m lies outside (north of) the levee that delineates the north side of main body of Northeast Point debris-avalanche deposit (unit *IHa*). The seaward part of this unit north of the levee is relatively nonhummocky and called here Northeast Bench. By this morphology the unit underlying the bench is interpreted as a lahar deposit (unit *IHl*). But more than 200 m back from the sea cliff the area outside levee is nearly as hummocky as that south of the levee, and thus is also mapped with unit *IHa*. Both map units (units *IHl* and *IHa*) are overlain by a tephra sequence with tephra H at its base. The flattish seaward-sloping part of this area delineating the bench may be a laharic phase that issued from the debris avalanche.

Sandy gravel lacking large blocks underlies H? tephra atop the Pleistocene landslide block (unit *Pl*) on south side of island. It may be contemporaneous with Northeast Bench lahar(?) deposit.

Deposits Between H and C Tephras (1400–1100 yr B.P.)

South Point debris-avalanche deposit (unit *HCas*)

South Point, which juts 0.6 km seaward of the general line of the south coast, consists of a diamict of angular clasts of porphyritic andesite as large as 6 m in intermediate diameter. Its hummocky surface has local relief of 10 m. Clearly a debris-avalanche deposit, it has no discernible levees upslope, where it has been deeply buried by younger eruption deposits, especially in 1963–64.

Like the geomorphic relation at Northeast Point, the South Point debris avalanche overrode and partly buried a sea cliff that now lies 200 m back from South Point. The sharply hummocky topography is similar both seaward and behind the arrested sea cliff. The present sea cliff (seaward of buried one) is 30 m high, the minimum thickness of South Point debris-avalanche deposit there. That South Point is far broader and projects much farther seaward than Northeast Point suggests the latter's greater age, consistent with tephra stratigraphy.

The tephra-and-humus sequence that overlies the debris-avalanche deposit ranges from 0 to 8 m thick, typically 1–2 m thick, having the C tephra at its base. Though this is the youngest of the large debris avalanches forming Augustine's south and east coast, it too is eroded back into a high cliff. It is thus geomorphically much older than any of the uncliffed debris-avalanche deposits on the northwest and north coasts.

Long Beach debris-avalanche deposit (unit *HCal*)

A hummocky diamict is sparsely exposed in the distal southwest quarter as small kipukas surrounded by 1976 and older pumiceous lahar deposit and as an uninterrupted hummocky belt just beyond the limit of 1976 deposits. The hummocks are as much as 9 m high and 20 in diameter, one of the largest consisting mostly of one 9-m andesite boulder. Numerous large boulders protruding through swampy terrain near the southwest coast probably are of this deposit. A lithic diamict exposed along Long Beach also includes hummocks exposing boulders as large as 6 m, capped by tephra layers C and M. Large boulders lie in matrix of smaller angular material of identical composition. Most of the lithic clasts are porphyritic andesite, but a few are sandstone. The avalanche must have flowed down across Jurassic sandstone (farther west than now exposed) en route to the coast. Detterman (1973) mistook the south-coastal exposure containing the 6-m boulder for *in-situ* lava flow.

At low tide and on aerial photographs, large-boulder lag can be seen as far as 0.5 km off the south-southwest and southwest shore; maps show highly convoluted bathymetric contours here extending to a depth of 10 m as far as 2 km offshore, some 8.5 km from the summit. Similar submarine hummocky topography extends generally 6 to 9 kilometers outboard of demonstrable debris-avalanche deposits on other azimuths: such topography off the southwest coast must record the seaward extent of debris avalanche.

In the southwest quarter 0.6 to 1.0 km back from the south coast is semicontinuous swamp nearly at sea level devoid of large hummocks but diversified by several large boulders. This low area may have been a lagoon inboard of a debris avalanche that swept mostly to sea—like Northwest lagoon now behind West Island (see below). Younger pyroclastic and laharic deposits, including from 1935, 1964, and 1976 eruptions, have nearly filled the former southwest lagoon. This much-buried Long Beach debris-avalanche deposit seems to extend a similar distance from the summit cone as the younger and well-preserved West Island debris-avalanche deposit (see below).

The Long Beach debris-avalanche deposit (unit *HCal*) is perhaps only slightly older than the overlying pumiceous deposit (Southwest pyroclastic fan, unit *HCpw*), for in exposures along the eastern part of Long Beach where the pumiceous deposit directly overlies the lahar there is no discernible soil at the top of the diamict.

Southwest pyroclastic-flow deposit (unit *HCpw*)

A pumiceous sandy diamict as thick as 16 m overlies the Long Beach debris-avalanche deposit and an associated lahar deposit (units *HCal* and *HClw*) and directly underlying C tephra in coastal cliffs of the southwest flank. The pyroclastic deposit is 75–80 percent sand matrix; among the coarser clasts three-quarters are pumice, one quarter lithics as large as 5 cm (rarely as large as 30 cm). The deposit is graded by density: pumice clasts are concentrated in upper 3 m of deposit, lithic clasts in lower 10 m, though rare lithics lie throughout the deposit. The upper 3 m of the deposit is pale red, oxidized from high temperature. It has all the characteristics of pumiceous pyroclastic-flow deposit.

Southeast pyroclastic-fan deposit (units *HCpe*, *HClc* and *HClp*)

On the south-southeast coast a pumiceous pyroclastic-flow deposit (unit *HCpe*) is exposed only in section in lower part of the sea cliff. Farther east at Southeast point a lithic pyroclastic-flow (and lahar?) deposit (unit *HClc*) consists of cobble gravel to sandy cobble gravel that is vaguely stratified and lacking in large boulders, suggestive of a laharic or pyroclastic-flow deposit. Upslope from Southeast Point a proximal facies (unit *HClp*) contains numerous angular lithic (dense) porphyritic-andesite boulders in 4–6 m range and a few as large as 9 m. Some smaller dense blocks are prismatically jointed, revealing that the flow originated as hot dome rock. Surface texture of both facies is coarsely lobate and leveed with a relatively gentle local relief as much as 2.5 m—the morphology not of debris avalanche but of lithic pyroclastic flow (or lahar?). The unusually large size of some blocks (for a pyroclastic-flow deposit) is due to the steep slope (24°) and short distance (2.2 to 3.2 km) between the summit and the deposit. Both the coastal and the proximal facies are overlain by the C tephra, the coastal facies underlain by the H tephra.

North Bench diamict (unit *IMan*)

North Bench diamict comprises angular porphyritic andesite fragments as large as 3.5 m, bearing a mildly hummocky topography with local relief of 5 m. Seaward the deposit is truncated by a gently arcuate wave-cut scarp as high as 23 m, the highest near-coastal topographic feature along the west and north coasts. This sea cliff is now isolated 340 to 460 m from the sea by younger deposits that have flowed coastwise in the manner shown in figure 6*C*. Begét and Kienle (1992) ignored the eastern part of this feature and lumped the western part with their Grouse Point debris-avalanche deposit. The North Bench bouldery diamict is probably a debris-avalanche deposit, but an origin by lahar or lithic pyroclastic flow cannot be disqualified.

North Bench diamict is geomorphically distinct from three neighboring debris-avalanche deposits (West Island, Grouse Point, Rocky Point) described below. The two segments of the arrested sea cliff truncating North Bench are nearly surrounded by these younger diamicts. A straight scarp behind West Lagoon partly buried by West Island debris-avalanche deposit (see below) may be a west extension of this sea cliff.

The North Bench diamict is overlain by a pyroclastic-flow deposit (undistinguished on map) and by the Katmai 1912 ash and two older sand ashes. This tephra stratigraphy is about the same as that overlying the nearby clearly younger debris-avalanche deposits such as at West Island and Grouse Point. But the geomorphic expression including a nearly continuous straight sea cliff of moderate height well back from present coast indicates a much older age of the North Bench diamict, perhaps in the HC or IH interval. Probably the overlying tephra stratigraphy is highly incomplete, perhaps because the veneering pyroclastic-flow deposit is itself much younger than the North Bench diamict. Thus the correlation chart shows this unit only very broadly constrained stratigraphically.

Deposits Between C and M Tephras (1000–700 yr B.P.)

Pyroclastic-flow deposit (unit *CMp*)

In a coastal gully 300 m west of Augustine Creek, a sandy pumiceous pyroclastic-flow deposit (unit *CMp*) 0–3 m thick underlies the M(?) tephra and overlies the thick, oxidized pumiceous pyroclastic-flow deposit of “Southwest pyroclastic fan” (unit *Hcpw*). One site reveals two massive deposits—a lower one 13 m thick with gas-escape pipes and an upper one 4 m thick—separated by 20 cm of apparently fluvial deposit lacking a paleosol. These flows probably followed Augustine Creek and spilled through a western swale. This unit, apparently scarcely eroded, pinches out about 0.5 km west of the creek: its overbank spillage was thus limited to the vicinity of present creek.

Lahar deposit (unit *CMl*)

A lithic lahar (unit *CMl*) as thick as 2.5 m poured down a broad paleoswale west of Southeast Point. Similar flows poured across the Jurassic bedrock block and channeled down Middle and East Kamishak Creeks to overtop part of South Point debris-avalanche deposit. At the mouth of Middle Kamishak Creek the deposit is eroded back into a sea cliff that descends east from 50 to 30 m high with the slope of the fan surface.

Deposits Between M and B Tephras (700–400 yr B.P.)

Lagoon debris-avalanche deposit (unit *MBal*)

Lagoon debris-avalanche deposit has a hummocky topography with local relief of 10 m and contains angular porphyritic andesite boulders at least as large as 3 m. In coastal exposures it is overlain by about 60 cm of organic debris and tephra, at whose base is a discontinuous pumice lapilli, apparently tephra B. The deposit has a conspicuous left-lateral levee built over a lithic pyroclastic-flow deposit (unit *MBp*) to the south, which is capped by tephra B and underlain by tephra M. Part of the hummocky Lagoon debris-avalanche deposit, though, lies outside (south of) this levee, which suggests that the avalanche arrived in at least two closely spaced pulses.

The West Island debris-avalanche deposit partly buries the north side of Lagoon debris-avalanche deposit, banked against an apparent sea cliff eroded into the Lagoon deposit. A nearly continuous sea cliff inside of Northwest Lagoon, overridden and modified by the West Island debris avalanche, is perhaps a segment of these same sea cliffs.

Pyroclastic-flow and lahar deposits (units *Mbplo, Mbpli, MBp,* and *MBpl*)

Atop a sea cliff now isolated along the inner margin of West lagoon is a 4-m massive cobbly sand, apparently lithic pyroclastic-flow (or lahar?) deposit (unit *MBplo*). It is capped by B(?) tephra, which at one site is underlain by M(?) tephra. Upslope at altitudes 40–90 m the deposit is far more bouldery and diversified by intricately lobate termini (unit *MBpli*). The outboard portion formerly extended at least 300 m seaward into West lagoon, its legacy a lag of boulders as large as 2.5 m. This wave erosion must have occurred during the M-B period, after which a growing sand spit enclosed the lagoon and isolated the sea cliff from ocean waves.

In Southwest swale a patch of unit MBp is flanked by a flatter surface mapped as *MBpl*).

Southeast Beach debris-avalanche deposit (unit *MBas*)

A bouldery diamict exposed in upper part of bluff along Southeast beach (unit *MBas*) is studded with angular *in situ* blocks as large as 2.5 m, as large as 6 m as lag on beach, and as large as 7 m in the surf zone seaward. The diamict is overlain by B tephra and underlain by M and C tephras. These tephras overlie unit *HCpe* that forms most of bluff. Adjacent lahar or pyroclastic-flow deposits (units *MBlp* and *MBp*) are flatter surfaced and contain angular lithic andesite clasts no larger than 2 m.

Deposits Younger than B Tephra (<350 yr. B.P.)

Grouse Point debris-avalanche deposit (unit *Bag*)

Grouse Point diamict is hummocky with local relief of 5 m and is composed of reddish porphyritic andesite including angular boulders at least as large as 2.5 m. Overlying stratigraphy in upward stratigraphic succession is lithic pyroclastic-flow deposit, possibly waterlaid (tsunami?) deposit, two thin ash layers, and the distinctive white Katmai 1912 ash.

At lowest tides a nearly continuous field of boulders extends nearly a kilometer seaward of the present beach. The deposit has been eroded back into a nearly continuous, sharply curving sea cliff 4–7 m high. Thus geo-morphically this deposit seems older than the similarly coarse and hummocky West Island and Rocky Point deposits but much younger than the South Point diamict and others on the south and east coasts. It may be an eastern arm of Lagoon debris-avalanche deposit.

Grouse Point debris-avalanche deposit covers part of the sea cliff cut into North Bench deposit. By this and its far more hummocky surface texture, Grouse Point diamict is geomorphically distinct from North Bench diamict. Also contrasting the arrested sea cliff of North Bench, Grouse Point deposit juts into the sea. Grouse Point deposit must be considerably younger than North Bench diamict.

Grouse Point diamict is not proven to predate the B tephra, exposed in gullies upslope from North Bench diamict (unit *IMan*). Begét and Kienle (1992) having not distinguished North Bench diamict from Grouse Point diamict, they inferred the Grouse Point as well as North Bench diamict to underlie the B tephra.

West Island debris-avalanche deposit (units *Bawi* and *Bawo*)

A diamict of brecciated andesite-dacite forms West Island, separated from the northwest coast of Augustine

Island by Northwest lagoon 0.5 km wide. The deposit is a mixture of angular to very angular reddish to grayish porphyritic andesite boulders as large as 4 m set in a nonsorted matrix of finer diamict. The West Island deposit comprises a central core of unmodified high conical hummocks as high as 30 m with slopes as steep as 40°, surrounded on seaward sides by a wide zone of lower hummocks (all unit *Bawo*). The hummocks are capped by 0–30 cm of humus and five sand ashes of which three underlie the Katmai 1912 white-silt ash. The B tephra is absent from West Island and thus the hummocky diamict must predate 350 yr B.P. (table 2). In a gully 1.2 km back from the lagoon at altitude 85 m, a landward phase of the deposit (unit *Bawi*) is underlain by the M(?) tephra (but B tephra is missing).

On the seaward side there is but a discontinuous sea cliff cut into sporadic hummocks, though the irregular cliff line is fairly straight. West Island deposit is thickly vegetated by shrub alder and a few spruce. A continuous field of boulders ranging up to 5 m in diameter extends at least as far as 1.3 km offshore, much of it visible at the lowest spring tides and discernable as well on aerial photographs.

Hummocks on the southwest side of West Island are nearly flat topped, apparently beveled down as much as 20 m. These southwestern hummocks are also sharply incised, and some of them capped by coarse winnowed lag of openwork boulders as large as 4 m. A few of them are overlain by poorly sorted sand, perhaps waterlaid, as high as 5 m above high-tide level. The geomorphically modified southwestmost hummocks are evidence of a great rush of water across them. This evidence of a huge flow of water perhaps records a great sea wave (tsunami) created as West Island debris avalanche plowed into the sea with high momentum. The modification could not have been caused by an 1883 tsunami originating from Burr Point because the low-level hummocky the north part of West Island (facing Burr Point) is unmodified and because at least one of the modified hummocks is overlain by tephra older than the 1912 Katmai ash.

One seaward hummock on the south part of the deposit attached to the main island is oddly overlain by pumice lapilli chemically identified with the M tephra (Begét, unpubl. data). Begét and Kienle (1992) and Siebert and others (1995) suggest that this whole area and perhaps also the southwestern fifth of West Island are part of Lagoon debris avalanche, overlapped by West Island debris avalanche. Yet the hummocks are sharp and continuous across the area, with no topographic hint of the boundary as shown by Siebert and others (1995, fig. 10). Perhaps the capping M tephra is a fragile clast brought down in the West Island avalanche, as rare fragile clasts containing pumice lie in parts of the Burr Point debris avalanche and 25–30-m dome blocks rode down to the coast in the Burr Point and Northeast Point debris avalanches.

A broad part of the lower northwest volcano flank landward of Northwest lagoon has probably only a veneer of the coarse West Island debris-avalanche deposit (unit *Bawi*) overlying similar bouldery rubble of Lagoon debris-avalanche or older deposit whose surface was extensively and broadly fluted by the overriding West Island avalanche. The fluting descends a sea cliff 8 to 15 m high (southeast coast of Northwest lagoon) that demarked Augustine's northwest coast just before the West Island avalanche. The inland facies (unit *Bawi*) is distinguished by a separate map symbol only because it is a veneer over older topography rather than a substantially thick new deposit as unit *Bawo*. Detterman (1973) mapped much of this landward area as *in-situ* andesite lava flow, but clearly the whole area is of nonsorted angular coarse rubble containing angular boulders as large as many meters. The area of the inland facies is in many places covered by dense scrub-spruce forest.

Rocky Point debris-avalanche deposit (unit *Bar*)

West of Burr Point, a diamict forms a sharp point of land (Rocky Point). The deposit has a sharply hummocky topography with a relief of 40 m and local slopes as steep as 35° and comprises angular andesite boulders at least as large as 5 m. At low tide this debris forms bouldery islands (unit *ob*) as far as 1.5 km offshore that have been winnowed and beveled to bouldery shoals. The Rocky Point deposit is about 80 percent covered by scrub alder but lacks the spruce covering parts of West Island and Lagoon debris-avalanche deposits. Upslope from the main deposit about Rocky point are vegetated debris levees as high as 15 m that seem to define the two sides of this debris avalanche.

Capping the coarse diamict in upward succession is weakly oxidized soil horizon 20 cm thick, an organic layer, a gray silt ash (1883 eruption?), and a distinctive white silt ash from the 1912 Katmai eruption. The irregular, curving sea-cliff line is roughly similar to that at West Island. The sharp morphology of the hummocks and that it has but one ash layer beneath the Katmai ash makes this deposit is both geomorphically and stratigraphically younger than the West Island debris-avalanche deposit.

Hummocks on the east side of the Rocky Point diamict are overlain by ash-cloud deposits of 1976 and 1986 eruptions. Alder was killed by these events, giving the hummocks an appearance of youth like those of the adjacent historic Burr Point hummocks. The coarse boulders and shoal jut 600 to 1500 m seaward from both the Rocky Point and Burr Point deposits. The boundary between the Rocky Point and Burr Point debris-avalanche deposits is drawn at a sharp reëntrant in this offshore coarse debris, where the debris becomes much finer and even at spring-low tide reaches only 200 m offshore.

North Slope lava flow (unit *Bln*)

A conspicuous lava flow on the middle north flank consists of massive porphyritic andesite ranging from light gray to oxidized light reddish brown. It contains about 10 percent plagioclase phenocrysts as large as 4 mm. The apex of the conspicuous landform at about altitude 650 m apparently marks the site of a flank vent, about 600 m below the present summit, indeed below the base of the entire summit-dome complex. The flow terminated 450 m below its apex at a distance of 1.75 km. Detterman (1973), perhaps confused by its veneer of angular rubble, mapped this body as “lahar-type mud”.

This lava flow is usually considered as the last part of the 1883 eruption (Kienle and Forbes, 1976; Siebert and others, 1987, 1989, 1995; Swanson and Kienle, 1988). Kienle and Swanson (1980) had called it “prehistoric” but gave no evidence. Overlying the upper east side of the lava flow is a sharp-crested ridge at least 640 m long and as thick as 15 m consisting of diamict including many angular fragments as large as 5 m of dome-rock porphyritic andesite. In any one small area of this deposit the andesite boulders are diversely black, reddish, and gray. This clearly mixed deposit is a debris-avalanche levee. The debris can be traced downslope to altitude 450 m, below which it is discontinuous but aligned with a sharp levee well defined below altitude 200 m, the west edge of the Burr Point debris-avalanche deposit (see below). The Burr Point debris avalanche occurred at or near the beginning of the 1883 eruption; the lava flow is older. The lava flow appears to be overlain by just one coarse diamict, and thus it must be younger than the Rocky Point debris avalanche, which would have swept down the lava flow had it then existed. The lava flow seems to show on Doroshin's (1870) sketch (see Kienle and Swanson 1980, fig.5; Kienle and others, 1987, fig. 2), though Siebert and others (1989, 1995) claim it doesn't show. The stratigraphic level beneath the Burr Point diamict and its position on the north flank suggest that the lava flow occurred late during an eruption that began with the Rocky Point debris avalanche.

A hypothetical alternative for its age is that North Slope lava flow began the 1883 eruption and was later overridden by the Burr Point debris avalanche. Problems with such a model include: (a) there is no evident baking of the base of the overlying debris avalanche as might have occurred had the lava been fresh and hot, and (b) a vent at mid-altitude on the flank should have provided the outlet for magma and relieved vent pressure, precluding injection of magma higher that would cause a debris avalanche later in the eruption.

Beach and Eolian Deposits (unit *bed*)

An area of about 1.5 km^2 lying 3 to 7 m above sea level on the southwest corner of Augustine Island comprises dozens of subparallel ridges. In form they are clearly a succession of accreted beach and back-beach eolian-dune deposits. A small wave-cut cliff into this deposit along West lagoon and several pits dug into it show that the ridges are mostly of well-sorted medium sand, apparently eolian deposit. Much of the landward half of this feature is mantled by about 30 cm of the M tephra, showing that the landward ridges predate about 750 yr B.P. Excavations are not deep enough to discover whether the C tephra lies deeper. The wave-cut exposure reveals the M tephra overlain by 3 m of eolian sand capped by Katmai 1912 ash. Ridges farther seaward seem devoid of M tephra. Thus the eolian-sand ridges seaward of a small north-draining estuary have accreted largely or entirely since 750 yr B.P.

HISTORIC DEPOSITS

1883 Eruption

Burr Point debris-avalanche deposit (unit *83a*)

A diamict about Burr Point consists of hummocks with relief as much as 30 m, the freshest such deposit on Augustine Island. The intricately hummocky topography and the seemingly random distribution of hummocks having steep (20–35°) sides strongly resemble the deposit of the great debris avalanche of Mount St. Helens of 18 May 1980 (Voight and others, 1981; Glicken, 1986, 1991). Brecciated andesite fragments compose the Burr Point hummocks; individual blocks are as large as 4 m. Some blocks are as large as 8 m; one slab at the Burr Point coast is 25 m long and at least 9 m thick. A few of these large blocks are highly fragmented but mostly intact, what Glicken (1986) calls “jig-saw” texture in the 1980 Mount St. Helens deposit. The matrix between blocks is comminuted andesite, an unsorted pebbly-sand diamict of diversely sized very angular clasts identical to the large blocks.

Several varieties of porphyritic andesite compose the blocks, which in many places are randomly thrown together: the gray with the reddish, the irregularly broken with the columnarly jointed. A few blocks as large as 4 m are of sintered vent spatter. Several hummocks contain hydrothermally altered (soft, yellow to brown) andesite, derived from within the former cone. A few hummocks also incorporate fragile clasts of fall pumice, apparently prehistoric beds that must have lain on the north flank before the 1883 eruption and were carried to the coast scarcely disrupted within the avalanche. Emplacement was thus clearly by nonturbulent flow that could carry fragile blocks like agglomerate and bedded pumice without disintegrating and assimilating them.

Some of the hummocks are overlain by an organic soil, which contains the distinctive white silt ash 1 to 3 cm thick of the 1912 Katmai eruption. Large boulders of some coastal hummocks have rapidly growing rugose lichen that by 1988–1990 had grown as large as 10 to 21 cm in diameter.

The north (seaward) sides and tops of many hummocks along the shore have admixed exotic pebbles of argillite, granite, gabbro, amphibolite, hornfels, and others, many of them affiliated with slabs of deformed mud as large as 1.5 m thick and 7 m long. Some of the mud clasts are rich in broken clam shells and contain rounded pebbles of felsite and vein quartz. Radiocarbon analyses of shells from two different hummocks gave ages of about 6210 and 7170 yr B.P. (table 2). The mud clasts are as much as 15 m above high spring tides and 13 m above storm high water registered by the upper limit of stranded driftwood and fishing floats. The mud clasts are slabs of bay mud scraped up by the debris avalanche as it plowed into offshore sediments, evidence that the avalanche was fast and energetic. That a moving avalanche can bevel off a layer of underlying debris and place it atop the moving debris is illustrated by some rocky snow avalanches (Waitt and others, 1994, fig. 14).

A conspicuous straight, sharp-crested lateral levee 3 to 10 m high containing blocks of porphyritic-andesite dome rock as large as 6 m marks the left (west) margin of the debris-avalanche path. The most upslope part overlies the North Slope lava flow at altitudes 700 to 450 m. Below altitude 200 m the east side of the levee is partly buried by, and the levee crest was in several places overtopped by, pumiceous pyroclastic flows during the 1976 and 1986 eruptions.

Across the area mapped as 1883 debris-avalanche deposit the hummocky topography is uninterrupted by intervening levees. We disagree with Siebert and others (1995) that the hummocky area about Burr Point comprises three separate deposits interpreted as evidence of successive, retrogressive failures of the summit. There is no levee to distinguish their central from eastern lobes, which cannot be separated by any lithologic or geomorphic criteria. And their “western lobe” of the deposit is instead the eastern side of the older Rocky Point debris-avalanche deposit (see above). The Burr Point diamict thus seems to be a single deposit.

Unlike the West Island debris-avalanche deposit, the Burr Point deposit is nearly devoid of vegetation and lacks sea cliffs, and thus it is clearly much younger. The hummocky topography about Burr Point is little if any sharper than that at Rocky Point. The overlying soil and organic layer reveal the greater age of the Rocky Point deposit compared to the adjacent similarly hummocky diamict about Burr Point. Both Burr Point and Rocky Point have offshore remnant islands, but those at Rocky Point are wave-beveled to rocky shoals, further establishing the relative antiquity of the latter.

Pyroclastic-flow and surge deposit (unit *83p*)

Overlying the Burr Point debris-avalanche deposit is a few centimeters of laminated silt ash, overlain by nonsorted pebbly sand 0 to 2 m thick, in turn grading up to a reddish-brown granular medium sand 5–10 cm thick. Near Burr Point the pebbly-sand phase is cut by vertical pipes 2–30 cm in diameter of intensely oxidized matrix-free lithic pebble gravel with clasts as large as 8 cm. The oxidation is orange to brown to yellow coatings on clasts, which suggests that these structures were rootless fumaroles. The deposit is interpreted as that of a pyroclastic flow or surge.

The pyroclastic deposit thins to nil over the debris-avalanche hummocks, smoothing the original relief of the debris avalanche by partly filling the lows. The deposit is thickest in the western and southern part of the hummock field and thins to a few centimeters at the eastmost coastal hummocks.

Discussion

In the wake of Augustine's 6 October 1883 eruption, Davidson (1884) from second-hand information reported dramatic changes to the volcano including a collapse of summit area to the north side. One of Davidson's sources, a Capt. Cullie of the Alaska Commercial Company at English Bay, inspected Augustine during close approach by ship in June 1884, recorded in an unpublished letter of 5 November 1884 from Davidson to the Director of the Coast and Geodetic Survey. Capt. Cullie reported that:

> *. . . from the summit a great slide of the mountain over half a mile broad had taken place towards the rocky boat harbor on the northnorthwestward. It appeared as if there had been a great sinking of the rocks under the summit leaving a face of wall overlooking the slide. Down this had poured the lava* [sic] *and erupted material to the base of the mountain and had pushed into the boat harbor and filled it up. In the upper part of lava* [sic] *outflow was issuing great volumes of white smoke . . .*

Three decades later Griggs (1920) briefly visited the north side of Augustine, also concluding that the hummocky deposit about Burr Point was the deposit of a great recent landslide. This debris slide doubtless caused the tsunami that, according to Davidson (1884), swept into English Bay harbor on Kenai Peninsula on the morning of 6 October 1883.

1935 Eruption

Lava dome (unit *35d*)

The remnant of a 1935 dome forms a prominent point on the north-northwest of the summit dome complex and a broad lobe that descends the west-southwest summit cone. Rock from the north-northwest point is gray porphyritic andesite. The 1935 dome is identified by several contemporaneous sources: (1) shipboard photographs taken by Kenai Peninsula resident Steve Zawis-towski in July 1935 showing the steaming west-southwest lobe; (2) USGS oblique aerial photographs taken in 1944 and 1959 by Bruce L. Reed and in 1960 by Austin Post, all before large changes occurred to the summit area during the 1963–64 and 1976 eruptions; and (3) Detterman (1968, 1973), who in 1967 distinguished in the field the new 1963–64 dome from remnants of older domes. The 1944, 1959, and 1960 photographs show a paired dome: one mostly inside the 1883 crater, the other outside the west-southwest rim.

Flank deposits (unit *35b*)

High on the southwest flank downslope of the 1935 dome heads a fan of rubble with angular andesite dome-rock boulders as large as 6 m. This material is similar to coarse pyroclastic-flow deposits on the south flank of the 1963–64 eruption. Because the southwest coarse fan lies beneath the 1935 dome, it is thought to have been emplaced then.

A July 1935 photograph from a boat off the southwest coast shows apparently fresh deposits in west-southwest swale downslope from the steaming, active dome. Some of the pyroclastic-flow deposits mapped with 1964 eruption may include similar debris of 1935 vintage.

1963–64 Eruption

The timing and behavior of an eruption between October 1963 and August 1964 is described by Detterman (1968), who mapped on the island in 1967 when those effects were fresh. The dome and south-flank deposits remain well exposed.

Lava dome (unit *64d*)

The 1964 eruption built a dome atop the summit that buried part of an old summit-dome complex that had been decapitated to form the 1883 debris avalanche. The 1963–64 dome flowed only 100–150 m down the south slope.

Pyroclastic-flow and lahar deposits (unit *64p*)

The south-southeast flank bears several swaths of rubble, the largest 2 km long and as wide as 1 km. The deposits consists of nonsorted angular rubble, generally boulder gravel, with clasts as large as 7 m but generally smaller than 3.5 m, comprising largely lithic (dome-rock) debris but also 5–15 percent pumice. The debris displays an intricate series of downslope trending paired levees, evidence of emplacement by pyroclastic flow or (and) debris flow. All these patches lie within the area of fresh 1964 deposits mapped by Detterman (1968, fig. 1). East of the eastmost kipuka exposing Pleistocene deposits, remnants of the coarse lithic 1964 flows are surrounded by and (or) veneered by finer and far more pumiceous 1976 flows, the map boundary between them in places arbitrary.

The deposit is readily distinguishable from adjacent 1976 deposits by the coarseness of 1964 deposit and its greater vegetation. The 1964 rubble is heavily but discontinuously coated by moss, has established blueberry with stems as thick as 0.7 cm, and a few starts of alder.

Ballistics

Large angular blocks of gray, slightly vesicular, porphyritic andesite lie scattered about upland surfaces of the middle and lower south and southeast volcano flanks, an area of 1964 ballistic fall denoted by Detterman (1968, fig. 1). At a distance of 2.2 km south of the 1964 dome summit, these blocks are 30 cm in diameter.

Computed using variable but low drag coefficients developed by Waitt and others (1995) for the 1992 eruptions of Mt. Spurr volcano, minimum ejection velocities for the southside Augustine ballistic blocks are between 150 and 170 m/s. Such velocities are well within the range generated by shallow but powerful explosions from other volcanoes during historic eruptions.

1976 Eruption

Augustine erupted explosively from 22 to 25 January 1976, and built a large summit dome in middle to late February and in middle April 1976. Pyroclastic flows descended several flanks during the explosive phase, and descended the north flank from the dome during growth episodes. Virtually all of the 1976 dome was incorporated by the 1986 dome or buried by 1986 spatter.

Pyroclastic-flow, surge, and lahar deposits (unit *76p*)

During field mapping in 1988–1993, vegetation readily distinguished pyroclastic-flow deposits of the 1976 eruption low on the volcano flanks from those of 1986. The 1986 flows were scarcely vegetated, only a few sprigs of grass and only the smallest starts of blueberry. The similar 1976 flows are covered as much as 15 percent by grass and contain ground-hugging blueberry plants with stems as thick as 0.5 cm. Aerial photographs at 1:24,000 scale taken in August 1976 show the distribution of pyroclastic flows just after the 1976 eruption. Comparing these airphotos to those taken in 1986 and 1990 further aid in distinguishing 1976 from 1986 flows.

Projecting beyond the north and northeast margins of 1986 pyroclastic flows, 1976 pyroclastic flows comprise two lithologic varieties: pumiceous ones that on the northeast were mobile enough to approach and even flow into the sea; and overlapping lithic flows later shed from the growing dome that are steeper and did not reach as far.

The pumiceous flows have intricately lobate marginal scarps 1.5 to 3 m high. On the northeast are two sets of overlapping pumiceous flows. These deposits contain many breadcrusted bombs, a few well banded. Lithic-rich flows on the northeast contain blocks as large as 6 m, have steeper surface gradients, did not reach the sea, and contain almost no pumice.

Beyond the limits of 1976 pyroclastic flows near Burr Point is a very fine sand to silt ash apparently of a 1976 pyroclastic surge (Kamata and others, 1991). It is separated from 1883 pyroclastic-flow deposit (unit *83p*) by as much as 18 cm of peat, which locally contains the Katmai 1912 ash.

Airphotos of 1976 show that on the north flank between Burr Point and west of Grouse Point, the swales mapped as 1986 deposit had a very similar distribution of 1976 pyroclastic flows and lahars, though the 1986 flows extended slightly farther and mostly or entirely buried the 1976 deposits.

In several swales the pumiceous pyroclastic flows emplaced during the early part of the 1976 eruption seem to have mixed with the winter snowpack enough to transform downslope into mixed flows or lahars (included within unit *76p*). Thus in the gully that enters the coast at East Point, above altitude 120 m the pumiceous 1976 deposits look like those of normal pyroclastic flows with pumice-rich broadly lobate termini 1–2 m high, feathering out on vegetated adjacent highs. But where the gully is narrow and sinuous in its last 900 m, the flow(s) had momentum to flow nearly straight, running 3 m up on sharp bends. The deposit contains uncharred wood and apparently no charcoal, evidence that it was cool. The apparently hot flows are nearly identical lithologically to the apparently cool ones, and the transition gradational. Distinctions between the two cannot be made systematically, so they are as one unit: “deposits of pyroclastic flow and lahar”.

1986 Eruption

Augustine volcano erupted between 27 March and 31 August 1986 and sent scores of pyroclastic flows down its north and northeast flanks while erupting a new dome in the summit area. The pyroclastic flows ranged from highly pumiceous to entirely lithic.

Lava dome and spatter (units *86d* and *86a*)

The 1986 dome (unit *86d*), gray to reddish plagioclase-porphyritic microvesicular andesite, forms the most conspicuous part of summit are viewed from the north. As the dome grew it incorporated the large dome that had been emplaced at the same site during the 1976 eruption. The present dome is thus a composite of the two. The map unit includes a tongue at the north base of the dome emplaced late in eruption that could be classed as lava flow. As it grew, the dome shed numerous lithic pyroclastic flows down the north and northeast flanks.

A crescent-shaped bench south of the dome underlain by spatter and blocky fragments, apparently agglutinate (unit *86a*), can be mistaken for remnant 1976 dome debris, but photographs by one of us (JK) taken before and after 1986 show that it built up during that eruption.

Pyroclastic-flow and lahar deposits (unit *86p*)

The largest pyroclastic flows of 1986 lost 1 km in altitude (from summit) while extending 4 km to the sea along the northeast and north margins of the 1883 debris-avalanche deposit. Of the flows that reached the sea on the northeast, at least 3 were emplaced in late March (Kienle and others, 1986; Swanson and Kienle, 1988). These deposits are 1-3 m thick, lobate, rich in pumice, and contain breadcrust bombs. They are overlapped by a later (late April and late August) sequence of steeper, entirely juvenile-lithic pyroclastic flows.

Pumiceous flows (unit 86pp)

Some pumiceous pyroclasic flows on the north flank reached the sea while others stopped well short of the coast and have steep margins 1-3 m high and unchanneled surfaces. Pumice is concentrated at the surface while at depth pumice clasts are sparse. Even highly pumiceous flows contain lithics as large as 1.5 m in distal reaches. The flow matrix is brownish granular medium sand, poorly sorted. The flows contain rare hydrothermally altered andesite blocks perhaps derived secondarily from 1883 debris-avalanche hummocks nearby. Where wave cut along the back of a beach on the northeast shore, the 1986 pyroclastic-flow deposit displayed vertical fines-free gas-escape pipes.

Lithic pyroclastic flows (unit 86pl)

While the dome was growing during latter part of 1986 eruption, small parts of the dome repeatedly collapsed to form small-volume pyroclastic flows whose gravel component is entirely lithic dome rock (porphyritic andesite), including blocks as large as 3 m, some of them banded. Lateral levees of some individual flows are 1 to 3 m high and traceable hundreds of meters upslope.

Hybrid flows and lahars

Along a lower north-flank swale (north of summit on azimuth 004) a pumiceous early pyroclastic-flow deposit merges downslope into an area where an underlying 1976 pumiceous flow deposit has been modified. That surface is beveled and channeled 1–3 m deep and winnowed large lithic boulders stranded or stacked against each other—a water-scoured surface discontinuously overlain by matrix-free large boulders and bouldery gravel. The lack of matrix between and atop boulders contrasts with laharic deposits at Mount St. Helens (1980–86), Redoubt volcano (1990), and Mt. Spurr (1992), most of which included abundant matrix (sand and fine gravel). Thus some early pumiceous pyroclastic flows must have swiftly melted snow to form relatively clear-water floods. These floods scoured earlier deposits and left gravel bars and lags of boulders. One of these scour-and-bar areas is in turn overlapped from upslope by a pumiceous steep-margined pyroclastic-flow deposit. The slightly later pumiceous flows, sweeping mainly over new pyroclastic-flow deposit, could not entrain and melt much snow. These deposits are lumped with unit *86pp*.

On the east side of this area an extensive early 1986 pumiceous flow that nearly reached the sea has properties hybrid between pumiceous pyroclastic flow and pumiceous lahar (also mapped with unit *86pp*). This pumiceous flow has low-relief (centimeters-high) margins, a low surface slope and relief, discontinuous subparallel narrow and shallow surface channels, delicate willow branches charred only at surface resting points, and areas of shallow explosion pits or collapse topography associated with openwork fumarolic pipes. In one sharp gully the pumice is concentrated in waterlaid bars. Such features show that the flow was relatively thin and cool yet highly mobile, collapsed and vented by melting of underlying snow, and was locally rilled and redeposited by free surface water.

Pyroclastic flows also melted snow on other flanks of the volcano in 1986. Small-volume pumiceous pyroclastic flows, some grading into lahars, descended gullies on the northwest and east flanks. Distinguishing the deposit of a pumiceous pyroclastic from that of a lahar of nearly identical composition it is not always straightforward. Thus these deposits are mapped with unit *86pp*. Between Rocky Point and west of Grouse Point several 1986 pumiceous pyroclastic flows and lahars reached the sea or nearly did, overlapping and veneering nearly identical 1976 pumiceous deposits.

Eolian Deposits (unit *e*)

At the back of most sandy beaches exposed directly to the sea and above high-tide level are one or more coastwise ridges of loose, well-sorted sand, material wind-winnowed from the adjacent beach. This deposit ranges from a discontinuous skim only a few decimeters thick to ridges 1 km and more long and as high as 8 m. Where the seaward side of a tall dune is opened by storm waves, internal stratigraphy shows at least several strata in places made clear by numerous interbeds 1–5 cm thick of ash and (or) peat. Thus at Rocky Point (second youngest debris-avalanche deposit) a 113-cm-thick section in a sand dune overlies beach cobbles that overlie planed-off debris-avalanche diamict. The dune, mostly of well-sorted medium sand (eolian), is interrupted by at least 8 ash layers and 3 peaty layers, the most conspicuous ash being the white-silt Katmai 1912 layer near top of section. The lower parts of such sections are clearly prehistoric, but they are too spottily exposed to be distinguished cartographically.

Beach Deposits (units *bs* and *br*)

The coast of Augustine Island is a nearly continuous beach ranging from bouldery headlands to secluded sandy coves to a long sand spit that forms the southwest part of the island. The map classifies beaches as either rocky or sandy. At and above the level beach deposits at the back of many beaches are jams of logs and diverse manmade flotsam, in places as much as 4.5 m above ordinary high tide.

The rocky beach deposits (unit *br*) typically consist mostly of cobbles to boulders. Some boulders are as large as 7 m but generally are 0.25 to 2.0 m in intermediate diameter and are largely submerged at high tide. Most gravel clasts are of porphyritic andesite and pumice, but southside beaches also have sandstone and shale fragments. Because the sea cliffs are defended against normal waves by the boulder lag and in many places by stranded large logs, erosion of sea cliffs and new contributions to the beaches must occur largely during exceptional winter storms.

Exotic pebbles (granite, granodiorite, quartz diorite, gabbro, porphyritic dikerocks, hornfels, quartzite, argillite, gneiss, greenstone, vein quartz) are a component of the gravel phase on south beaches downslope from Pleistocene drift that is plastered against the Jurassic bedrock. Some of the exotic stones derive from conglomerate beds within Jurassic sandstone. Exotic pebbles lie more sparsely on beaches on the east, north, and west sides of the island, though only on the south is there an apparent upslope source for them. The exotic pebbles probably derived from glacial drift that at the end of the Pleistocene blanketed all slopes of the volcano. Most of this material has been brought down to the shore in Holocene debris avalanches, and then over time winnowed out by waves.

The sandy deposits (unit *bs*) are loose medium sand to pebbly sand and locally to pebble and cobble gravel. In many places the sandy beach deposits surround numerous large boulders, which clearly are a lag deposit resulting from storm waves over time eroding far landward into debris-avalanche, pyroclastic-flow, or laharic deposits. Where 1986 pyroclastic flows are being rapidly eroded back, the local supply of sand thus large and winnowed-out material abundant and coarse (very coarse sand to granule gravel), sandy beach faces are as steep as 12–14 degrees.

COMPARISON TO PREVIOUS GEOLOGIC MAP

The present geologic map and supporting stratigraphic and geomorphic analysis of Augustine Island show vast differences from the previous geologic map (Detterman, 1973). The 1973 map shows most surficial deposits—excepting the obviously late historic—as “Pleistocene” or “Pleistocene and Holocene” in age. But the present map and report show all but a few inliers are late Holocene, younger than about 2200 radiocarbon years. The 1973 map labels extensive areas on east, south, and northwest coasts as in-situ “lava flows”, whereas the present map and report show these deposits to be bouldery debris-avalanche deposits. Conversely the one conspicuous, undeniable lava flow on Augustine Island is called on the 1973 map “volcanic mud”.

The largest changes in implied processes are the number and extent of hummocky diamicts, similar in form and apparently origin to the great May 1980 debris avalanche off Mount St. Helens volcano. All together at least twelve and perhaps thirteen debris-avalanche deposits are discernable in the late-Holocene stratigraphy and geomorphology of Augustine volcano. The youngest four lie on north coast: two of them (Grouse Point and Rocky Point) are rather small; two others (Burr Point and especially West Island) are much larger.

All the large debris-avalanche deposits identified on Augustine Island lie at the present coast and clearly extend some distance seaward, perhaps kilometers. The older ones have been eroded back hundreds of meters into tall sea cliffs.

SYNOPTIC IMPLICATIONS TO VOLCANIC HAZARDS

A justified analysis of hazards from Augustine volcano is beyond the scope of this report. The brief synopsis that follows is from an extensive and fully referenced but unreviewed, unpublished 1996 hazards analysis by this report’s three coauthors.

Because Augustine Island is uninhabited, no one but the occasional visitor is at risk from many of the hazards Augustine volcano would otherwise present. During the late Holocene, pyroclastic flows and surges, lahars, and debris avalanches have swept repeatedly down all flanks to the sea; several falls of coarse tephra and coarse ballistic ejecta also have descended onto most of the island. Yet with no population or significant buildings to affect, there is no one and no thing at risk from these hypothetically damaging processes.

But not all of Augustine’s volcanic processes are confined to the island. Hot pyroclastic surges can sweep over sea water and kill on distant shores, the best-known historic example having been during the large 1883 eruption of Krakatua, Indonesia. Augustine being a relatively small stratovolcano, pumiceous pyroclastic surges from it could extend to sea and affect boats probably no farther than about 4 km off the island’s coast. Far less likely, a large lithic pyroclastic surge attending a rare debris avalanche—like that which swept from Mount St. Helens on 18 May 1980—could sweep as far as 8 km from Augustine’s shores.

Typically once every many eruptions—once every 150–200 years or so—Augustine’s summit-dome fails as a debris avalanche that flows into the sea. The most recent of these in 1883 caused a tsunami 6 m high (by historic record), perhaps higher, at English Bay on west shore of Kenai Peninsula 90 km east of Augustine Island. Although in the last two millennia Augustine has shed several debris avalanches to the sea like that of 1883, almost no geologic evidence of tsunami is known from the shores of southern Cook Inlet, despite searches for them in 1991 and 1993. Yet there is no known geologic evidence of the undeniable 1883 tsunami. Large boulders thrown up and back from the sea at Bede Point 6 km south of English Bay may record a tsunami some centuries old. While tsunami is a concern, the extent of hazard to coastal communities in southern Cook Inlet is debatable.

An Augustine eruption typically includes a plume of ash that drifts to mainland areas, as occurred during its two most recent eruptions (1976 and 1986). The largest hazard would be to aircraft. About 80 percent of the time prevailing winds carry such ash to the northeast and southeast quadrants.

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